

## **APPENDICES**

THE APPENDICES INCLUDE A BRIEF DESCRIPTION  
OF OUTREACH ACTIVITIES BY THE FUNDAMENTAL  
PHYSICS PROGRAM, AN OVERVIEW OF THE PRO-  
GRAM WRITTEN FOR A GENERAL AUDIENCE, AND  
A LIST OF ACRONYMS.

## APPENDICES

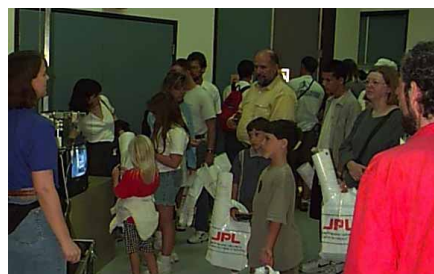
### Outreach

Part of the NASA charter is to communicate the goals and the results of its scientific investigations to the citizens of the United States. The fundamental physics program at JPL proactively maintains a level of outreach activity to perform this directive.

Members of the JPL team prepare demonstrations of the behavior of materials at low temperature for display at schools, at fairs, and at other public forums. The JPL team participates each year in the JPL Open House, inviting visitors to tour our low-temperature laboratories to view displays describing the flight experiments and to see the demonstrations of cryogenic phenomena. Tens of thousands of citizens visit the low-temperature labs over the two-day summer weekend of the Open House.

The fundamental physics team at JPL sponsors and supports an educational initiative to develop improved scientific instructional materials for middle school students. In cooperation with the Caltech Pre-college Science Initiative, team members have helped to produce instructional modules in subjects that relate to our area of scientific studies.

Additionally, the investigators in our program are encouraged to speak at public forums to describe their research and its benefits. While most often the presentations are to groups of their scientific peers, frequent examples of outreach to school children at the primary, middle school, and high school levels are reported. Members of the JPL team also prepare, or help to prepare, documents for public distribution describing the activities in our program.



*The JPL team participates in JPL's annual Open House with exhibits and demonstrations. Informal conversations with visitors include answering questions and describing NASA fundamental physics research in space.*

## **Science for Everyone: The Fundamental Physics Program Explained**

### **Two Quests: Seeking Knowledge Through Fundamental Physics**

Science is driven by humankind's curiosity about nature. In fundamental physics, scientists want to uncover and understand the basic underlying principles that govern the behavior of the world around us. Fundamental physics therefore provides a foundation for many other branches of science and establishes the intellectual underpinnings needed to maintain and further develop our high-technology society. We have two burning quests that motivate our laboratory research and beckon us to do experiments in space.

First, we seek to explore and understand the fundamental physical laws governing matter, space, and time. By looking deeply into the smallest and largest pieces that make up the fabric of our universe, we will understand better our basic ideas that describe the world. Several questions need our research answers:

- How broadly applicable is general relativity? Where could this theory break down?
- What is the nature of black holes? What can gravity waves tell us about the evolution of the universe?
- How can quantum theory be reconciled with gravitation?
- Do all bodies fall similarly, regardless of their makeup? Do all clocks keep the same time?
- Are there new forces yet to be discovered?

Second, we seek to discover and understand the organizing principles of nature from which structure and complexity emerge. While the basic laws of nature may be simple, the universe that has arisen under these laws is amazingly complex and diverse. By studying nature apart from Earth's gravity, we can understand better how the universe developed. Several questions need our research answers:

- Can the simple elegance of fundamental theories be applied to complex systems?
- Is the renormalization group technique valid under all unique conditions?
- How do finite size and nonequilibrium conditions alter the properties of matter?
- How can we use quantum effects for practical devices? What are the limits of the resolution of such devices?
- What is the role of symmetry (order) in establishing self-organized or chaotic behavior?
- How does broken symmetry give rise to complex patterns?

To find the answers to these questions, we pursue campaigns on three topics in modern physics. As we push out into the uncharted territory of testing new theories, we will draw closer to the essence of knowledge that describes how our universe works.

### **Campaign 1: Gravitational and Relativistic Physics**

Gravitational and relativistic physics is perhaps the most fundamental area of physics. Physicists have determined that there are four kinds of forces that operate on matter: gravity, electromagnetism, and the “strong” and “weak” forces within atoms. Gravity is the weakest of these forces, yet paradoxically the most dominant because it can act from very large distances. In fact, every bit of matter in the universe is under the influence, even if infinitesimally so, of every other bit of matter.

Relativity theories propose that gravitational forces apply equivalently to all bodies. Furthermore, Einstein’s theory of general relativity puts gravity at the heart of the structure of the universe, proposing that even the orderly space–time structure of the universe can be “warped” near a body of large mass — such as the Sun or even Earth. Even clocks would be affected by this warp. While these changes to the very fabric of space and time near a large body are dramatic in their importance, they are also very subtle and difficult to measure accurately. Yet, they must be taken into account even in routine astronomy observations and in measuring the position of satellites and planets. Advanced technologies must be used to detect and characterize these minute changes, so that the corrections due to relativistic phenomena can be precise.

Several missions and experiments designed to improve the accuracy of measurements of these effects are planned or proposed. All of them make use of the large mass of the Sun — or of Earth — to measure the distortion to space–time caused by these large bodies. This can be done only by getting away from the pull of Earth’s gravity. Example missions include:

- Gravity Probe-B will place ultrahigh-precision gyroscopes in an orbit over Earth’s poles in order to measure how space around Earth is altered by the planet itself. Both the “warp” caused by Earth’s mass and the “frame dragging” caused by Earth’s rotation will be measured.
- The Satellite Test of the Equivalence Principle will carry precision instruments to compare the gravitational and inertial mass of two test samples. Einstein’s equivalence principle proposes that these two masses should be identical, but only the most accurate of measurements can validate this.
- The Superconducting Microwave Oscillator will place a high-precision clock (a source of constant-frequency radio waves) in Earth orbit to test Einstein’s prediction that time varies depending on the strength of gravity. The clock rate will be measured at different positions around Earth and at different levels of the local gravitational field.
- The Gravitational Wave Mission will place three satellites in space. Although separated by more than one million kilometers, these satellites will be linked together by

onboard laser interferometers to measure tiny variations in distance — thus testing for the presence of the gravity waves predicted by general relativity.

- The Spacetime Mission will fly a satellite carrying a group of atomic clocks close to the Sun. These clocks, measuring time using different atomic compositions, will be compared with each other to determine the effect of the Sun's large gravity on their timekeeping.

### **Campaign 2: Laser Cooling and Atomic Physics**

While gravitational and relativistic physics examines the most fundamental laws describing the universe on the large scale, it is equally important to look at the tiny building blocks of matter and how they manifest the same fundamental laws. Atoms are the smallest systems in which we can study the basic principles of the universe. New techniques allow us to use laser light to cool and probe individual atoms, as a starting point for our exploration. By carefully working with individual atoms, we stand at the bridge between the smallest pieces of matter and the complex behavior of large systems. Furthermore, conducting these experiments in space allows us to remove the influence of gravity and manipulate matter freely, without having to counteract specimens “falling” within the instruments. By then observing the behavior of atoms completely under the experimenter's control, we have the promise of novel results and new insights previously hidden from view in Earth-bound laboratories.

In our space experiments, we can study clouds of atoms, cooled by laser light to very near absolute zero, yet freely floating without the forces that would be needed to contain them on Earth. This allows measurements of higher precision and longer observation times. Example experiments include:

- Laser-cooled clock experiments will deepen our understanding of the basis of time. A second in time is defined by the energy released by the vibration of cesium atoms; atomic clocks on Earth measure this vibration with high precision but always under the influence of gravity. By operating an atomic clock in space, we can improve our definition of time and the accuracy of timekeeping.
- Measurement of ultracold cesium atoms in an electric field will show how the atoms interact with that field. This measurement will reveal any asymmetries of charge that would be hidden from view by gravity in an Earth-bound laboratory. This experiment will test the Standard Model of physics that unifies all known forces of nature — except gravity — into a common theoretical description.
- Bose–Einstein condensation is a remarkable new state of matter that occurs when atoms are cooled down so much that the small amount of vibrational energy they have remaining becomes coherent (the waves have a constant difference in phase) throughout the sample. This condensate has been formed in Earth-bound laboratories, but always under the influence of gravity where the small variations in density, temperature, and composition limit the size and duration of the sample. An orbiting experiment will permit observation of a wider range of specimens, leading to a more comprehensive understanding of this unique phenomenon.

- An atom laser in space furthers the study of Bose–Einstein condensates by carefully controlling the condensed matter to emit coherent pulses of atoms. An atom laser was first demonstrated in 1997, but can be understood better in space where the matter pulses are not affected by gravity.
- A matter-wave gyroscope using laser-cooled atoms could be 100 times more accurate than a conventional gyro in measuring rotation and acceleration. This precision will allow orbiting instruments to measure Earth with much greater accuracy, as well as to enable more precise testing of gravitation and relativity theories.

### **Campaign 3: Low-Temperature and Condensed-Matter Physics**

The condensed phase of simple gases provides a unique testbed for the predictions of fundamental theories. Particular combinations of pressure and temperature yield a “critical point” where there is no distinction between different phases of matter. For example, at a liquid–vapor critical point, the difference between the liquid and vapor phases disappears. This unusual behavior is inherent in the properties of ordinary gases and other substances. Many of these phenomena can best be studied at low temperatures where thermal noise is much reduced. By understanding the complex critical behavior of low-temperature materials, such as liquid helium, we will learn more about critical properties of metallic alloys, magnetic materials, groups of fundamental particles, and larger-scale phenomena such as the percolation of water or the movement of weather patterns. The unique properties near critical points can also be used to prepare samples in well known conditions to test effects of a boundary on matter and to study nonequilibrium phenomena.

Because critical behavior is a function of not only temperature but pressure as well, the pressure must be uniform throughout the sample under observation. But gravity causes a difference in pressure in a sample, so the critical phenomena can be observed only in a very small region. If an experiment is conducted in space, the pressure can be uniform across the sample and much more comprehensive measurements can be made. Furthermore, a drop of sample can be freely suspended, without the interference of a container. This freedom from external constraints is not possible in an Earth-bound laboratory. Experiments exploring the physics of low temperature and condensed matter include:

- Critical Dynamics in Microgravity will closely study a sample of helium at the critical transition point between two phases of liquid helium. A small heat current will be applied to allow studies of nonequilibrium phenomena.
- The Microgravity Scaling Theory Experiment will measure many properties of helium at the critical transition from liquid to gas. The measurements will be used to determine scaling relations between the different properties.
- The Superfluid Universality Experiment will test the principle that some key properties of matter are invariant (universal) under a wide range of conditions. Helium near the critical point is used for this study.

- Experiments Along Coexistence Near Tricriticality will perform a rigorous examination of helium mixtures at the critical point where normal liquid, superfluid, and instability can coexist.
- Boundary Effects on the Superfluid Transition will provide the first test of the theory describing the effects of size and solid boundaries on thermal flow near a phase transition from one state of matter to the next.
- The Superfluid Hydrodynamics Experiment will examine isolated drops of superfluid helium floating freely in space. By eliminating the effects of walls or other perturbing surfaces, this experiment can provide ideal conditions for studying the behavior of the superfluid.
- Kinetics of Superfluid Phase Transitions will study the transition of superfluid helium between the solid and liquid phases. High-speed cameras will record the very beginning of these transitions in order to understand how they start and then spread through a material.

## ACRONYMS

<b>AMS</b>	Alpha Magnetic Spectrometer
<b>BEC</b>	Bose–Einstein condensation
<b>BECs</b>	Bose–Einstein condensates
<b>BEST</b>	Boundary Effects on the Superfluid Transition
<b>CHeX</b>	Confined Helium Experiment
<b>CVX</b>	Critical Viscosity Experiment
<b>DOE</b>	Department of Energy
<b>DYNAMX</b>	Critical Dynamics in Microgravity Experiment
<b>EDM</b>	electric dipole moment
<b>EDM-X</b>	Electron Dipole Moment Experiment
<b>ESA</b>	European Space Agency
<b>EXACT</b>	Experiments Along Coexistence Near Tricriticality
<b>GP-A</b>	Gravity Probe–A
<b>GP-B</b>	Gravity Probe–B
<b>GR</b>	general relativity
<b>GRP</b>	Gravitational and Relativistic Physics
<b>IML-1</b>	International Microgravity Laboratory–1
<b>IML-2</b>	International Microgravity Laboratory–2
<b>JPL</b>	Jet Propulsion Laboratory
<b>KISHT</b>	Kinetics of the Superfluid Helium Phase Transition
<b>LACE</b>	Laser-Cooled Clock Experiments
<b>LAGEOS I &amp; II</b>	Laser Geodynamics Satellite I & II
<b>LCAP</b>	Laser Cooling and Atomic Physics
<b>LIRE</b>	Laser Interplanetary Ranging Experiment
<b>LISA</b>	Laser Interferometer Space Antenna
<b>LLR</b>	Lunar Laser Ranging
<b>LMLV-1</b>	Lockheed Martin Launch Vehicle–1
<b>LOX</b>	liquid oxygen
<b>LPE</b>	Lambda-Point Experiment
<b>LTCM</b>	Low Temperature and Condensed Matter
<b>LTCMP</b>	Low-Temperature and Condensed-Matter Physics
<b>LTMPF</b>	Low-Temperature Microgravity Physics Facility
<b>M1</b>	Mission 1
<b>M2</b>	Mission 2
<b>MISTE</b>	Microgravity Scaling Theory Experiment
<b>MOT</b>	magneto-optical trap
<b>MRI</b>	magnetic resonance imaging
<b>NASA</b>	National Aeronautics and Space Administration
<b>OMEGA</b>	Orbiting Medium Explorer for Gravitational Astrophysics
<b>PARCS</b>	Primary Atomic Reference Clock in Space
<b>PNC</b>	parity nonconservation
<b>RACE</b>	Rubidium Atomic Clock Experiment
<b>RG</b>	renormalization group
<b>SAL</b>	Space Atom Laser
<b>SEE</b>	Satellite Energy Exchange
<b>SHE</b>	Superfluid Hydrodynamics Experiment
<b>SMW-G</b>	Space Matter-Wave Gyroscope
<b>STEP</b>	Satellite Test of the Equivalence Principle
<b>STM</b>	Spacetime Mission
<b>SUE</b>	Superfluid Universality Experiment
<b>SUMO</b>	Superconducting Microwave Oscillator
<b>TCP</b>	tricritical point
<b>ZENO</b>	Critical Fluid Light-Scattering Experiment